

# Study on CEPC performances with different collision energies and geometric layouts <sup>\*</sup>

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**Abstract:** Circular Electron-Positron Collider(CEPC) is one of the largest plans in high energy physics study at China, which would serve as Higgs Factory firstly and then upgrade to a hadron collider. In this paper we give the 50km and 100km design in both single ring and double ring schemes, including  $Z$  boson and  $W$  boson and Higgs boson by using the optimized method. Also, we give the potential of CEPC running at  $Z$  and  $W$  poles. And we analysis the relationship of luminosity with circumference and filling factor, which gives a way to evaluate the choice of geometry. What's more, we compare the nominal performance of CEPC-SPPC and LHC and FCC.

**Key words:** Circular Electron Positron Collider (CEPC), parameter design, geometric layouts

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## 1 Introduction

After the discovery of Higgs boson on LHC in 2012, it is natural to measure its properties as precise as possible, including mass, spin, CP nature, couplings, and etc. Compared with the International Linear Collider(ILC) working at 250GeV, a circular  $e^+e^-$  collider serving as Higgs Factory seems possible due to the low mass of Higgs. And the circular scheme has the potential to upgrade to a hadron collider for high energy frontier study. There are two ambitious international plans, one is called TLEP(renamed to FCC-ee later) at CERN aiming at constructing a 100km circular Higgs Factory, the other one is a 50km scheme starting from IHEP in Beijing.

Circular Electron-Positron Collider(CEPC) is one of the largest plans in high energy physics study at China, which would serve as Higgs Factory firstly and then upgrade to a 70-100TeV Super Proton-Proton Collider(SPPC) in the same tunnel. The goal of the CEPC is to provide  $e^+e^-$  collisions at the center-of-mass energy of 240GeV where the Higgs events are produced primarily through the interaction  $e^+e^- \rightarrow ZH$  and to deliver a peak luminosity greater than  $1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$  per IP[1].

$Z$  boson and  $W$  boson were discovered at LEP, which have made a great contribution to particle physics. As a  $e^+e^-$  collider, CEPC works as a  $Z$  or  $W$  Factory would be another interesting story. We use an optimized method[2] for parameter choice and compare the results of 50km scheme with 100km imagine in both single ring and double ring designs, which covers the energy region from  $Z$ -pole to  $t$ -pole. We analysis the relationship of lu-

minosity with circumference and filling factor to evaluate the geometry choice. A comparison of nominal performance of CEPC-SPPC and LHC and FCC is also shown.

## 2 Optimized method in parameter choice

The performance of a circular  $e^+e^-$  collider is connected with luminosity, which could be expressed as

$$L[\text{cm}^{-2}\text{s}^{-1}] = 2.17 \times 10^{34} (1+r) \xi_y \frac{eE_0[\text{GeV}] N_b N_e}{T_0[\text{s}] \beta_y^*[\text{cm}]} F_h \quad (1)$$

where  $r = \frac{\sigma_y}{\sigma_x}$  is the aspect ratio of the beam at IP,  $T_0$  is the revolution period,  $\beta_y^*$  is the beta function at the IP,  $\xi_y$  is the vertical beam-beam tune shift,  $N_b$  is the bunch numbers and  $N_e$  is the population of particle number in one bunch, and the  $F_h$  is hour glass effect expressed as

$$F_h = \frac{\beta_y^*}{\sqrt{\pi} \sigma_z} \exp\left(\frac{\beta_y^{*2}}{2\sigma_z^2}\right) K_0\left(\frac{\beta_y^{*2}}{2\sigma_z^2}\right) \quad (2)$$

where  $K_0$  is the zero order modified Bessel function of the second kind. From eq.(1), it is the beam-beam tune shift that has a significant influence on the luminosity of a collider directly.

An optimized method has been well studied in [2], which has taken several important effects into consideration, such as beam-beam limit coming from beam emittance blow-up, beam lifetime and energy spread limit constrained by beamstrahlung, and so on. Each particle in a beam will feel a strong nonlinear force when the beam encounters the counter rotating beam, which has

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deleterious effects on the dynamic behavior of the particle. Within this interaction, the particles will suffer from additional heatings, which would cause beam emittance blow-up. This emittance blow-up mechanism has been studied in [3, 4], one could get the beam-beam limit expressed as:

$$\xi_y \leq \frac{2845}{2\pi} \sqrt{\frac{T_0}{\tau_y \gamma N_{IP}}} \quad (3)$$

where  $N_{IP}$  is the number of interaction point,  $\tau_y$  is the transverse damping time and  $T_0$  is the revolution time.

Beam lifetime is determined by beamstrahlung in a high energy storage ring collider [5]. In order to achieve the beam lifetime as long as 30 minutes, one should guarantee the relationship between the bunch population and beam size satisfying

$$\frac{N_e}{\sigma_x \sigma_z} \leq 0.1 \eta \frac{\alpha}{3 \gamma r_e^2} \quad (4)$$

where  $N_e$  is the bunch population,  $\sigma_x$  and  $\sigma_z$  are the horizontal and longitudinal beam size at IP,  $\alpha$  is the fine structure constant,  $r_e$  is the electron classical radius and  $\eta$  is the energy acceptance of ring.

Taking eq.(3) into eq.(1), one acquires a relationship between luminosity and several key parameters of a collider

$$L_0 [\text{cm}^{-2} \text{s}^{-1}] = 0.7 \times 10^{34} \frac{1+r}{\beta_y^* [\text{cm}]} \sqrt{\frac{E_0 [\text{GeV}] I_b [\text{mA}] P_0 [\text{MW}]}{\gamma N_{IP}}} \quad (5)$$

$$L [\text{cm}^{-2} \text{s}^{-1}] = L_0 F_h \quad (6)$$

where  $E_0$  is the beam energy,  $I_b$  is the average beam current,  $P_0$  is the synchrotron radiation,  $N_{IP}$  is the number of interaction point and  $L_0$  is the peak luminosity. From eq.(5), it tells us that the synchrotron radiation power is one of the pivotal parameters to the luminosity of a circular  $e^+e^-$  collider. Obviously, when one tries to reduce the synchrotron radiation power, it might have deleterious effects on the luminosity.

According to the expression of  $U_0 = 88.5 \times 10^3 \frac{E_0^4 [\text{GeV}]}{\rho [\text{m}]}$ , there are two ordinary ways to reduce the synchrotron radiation, one is to make the machine working at lower energy, and the other one is to enlarge the bending radius. The former way leads to the plan of making CEPC severing as a  $Z$  or  $W$  factory, while the latter one puts forward a question: whether a 100km scheme (like FCC-ee) is better or not. Next, we will show the results by using the optimized method.

### 3 Study on CEPC in different collision energies and geometric

When restricting the synchrotron radiation power no more than 50MW, we give the parameters choice for CEPC in both 50km scheme and 100km imagine and

compare the performance of double ring design with single ones. And, the potential of CEPC serving as  $Z$  and  $W$  factories are included. What's more, higher energy run in  $\bar{t}\bar{t}$  of 100km imagine are also taken into consideration. All the results are listed in TABLE 1. At this stage, we only consider all the bunches are equal around the ring and the collider is at head-on collision.

## 4 Discussion

There are many interesting topics in a circular collider ring design. Next, we will discuss three aspects about the CEPC design.

### 4.1 Single ring v.s. two ring in CEPC baseline design

Two beam pipes are adopted by many  $e^+e^-$  machines, such as BEPC-II, PEP-II, KEKB and DAFNE, because high luminosity could be achieved within a large number of bunches. However, when constraining the synchrotron radiation power no more than 50MW, the average beam current is restricted at the same time because the energy loss from synchrotron radiation is the same within a certain geometry. When choosing the bunch number  $N_b$  and particle population  $N_e$  with a reasonable value, the luminosity of CEPC running as a Higgs factory in both one beam pipe and two are the same. Because from eq.(5), one could find that the luminosity is proportional to  $\sqrt{P_0}$  when fixing the other parameters. It is an economic choice to take one ring scheme for a Higgs factory.

### 4.2 Potential of CEPC running at $Z$ or $W$ poles

There is an active interest in a high-luminosity run of CEPC at the  $Z$  and  $W$  poles. Due to lower energy of  $Z$  and  $W$ , the synchrotron radiation in  $Z$  and  $W$  poles is much lower than a Higgs factory. We give the results of the parameters directly in TABLE 2. It tell us that more than 220 bunch numbers are needed in  $Z$  pole to achieve luminosity as high as  $1 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$  while 60 bunches are enough for  $W$  pole to reach the same luminosity. Though the synchrotron radiation power in  $Z$  pole is far away from 50MW, it is beyond imagination to arrange 220 equal bunches around the ring within Pretzel Orbit. It is a vain hope to achieve a high luminosity of  $1 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}$  in  $Z$ -pole with a 50km single ring design of CEPC within equal bunches and head-on collision, because electrostatic separators would be full of the ring to separate about 2200 bunches and the pretzel orbit would be too complicated. A bunch train scheme[6] seems hopeful to avoid this problem. However, it will make the length of the interaction regions longer and the machine-detector interface(MDI) design more complicated. So under these considerations, two beam pipes seems better.

Table 1. Comparing 50km and 100km CEPC design within single ring and double ring scheme.

Parameters	50km CEPC design						100km CEPC design							
	Single ring scheme			Double ring scheme			Single ring scheme				Double ring scheme			
	Z	W	H	Z	W	H	Z	W	H	$t\bar{t}$	Z	W	H	$t\bar{t}$
Beam energy $E$ [GeV]	45.5	80	120	45.5	80	120	45.5	80	120	175	45.5	80	120	175
Circumference $C$ [km]	50	50	50	50	50	50	100	100	100	100	100	100	100	100
Number of IP $N_{IP}$	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Bending radius $\rho$ [km]	6.094	6.094	6.094	6.094	6.094	6.094	10	10	10	10	10	10	10	10
SR power/beam $P$ [MW]	0.89	10.32	50	50	50	50	0.615	8.35	50	50	50	50	50	50
SR loss/turn $U_0$ [GeV]	0.062	0.6	3.01	0.062	0.6	3.01	0.038	0.36	1.84	8.3	0.038	0.36	1.84	8.3
Ring's Energy acceptance $\eta$	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Magnetic rigidity $B\rho$ [T·m]	151.8	266.9	400.4	151.8	266.9	400.4	151.8	266.9	400.4	584	151.8	266.9	400.4	584
Momentum compaction factor $\alpha_p$ [ $10^{-5}$ ]	0.364	1.527	0.729	0.364	1.527	0.729	0.453	0.371	0.196	0.117	0.453	0.371	0.196	0.117
Lifetime due to radiative Bhabha scattering $\tau_L$ [hour]	8.26	2.67	1.19	8.26	2.67	1.19	17.6	5.7	2.55	1.19	17.6	5.7	2.55	1.19
Beam current $I$ [mA]	14.23	16.8	16.6	796.81	84.04	16.62	16.21	23.02	27.63	5.96	1317	138.1	27.63	5.96
Bunch number $N_b$	48	48	48	2688	240	48	192	192	192	48	15600	1152	192	48
Bunch population $N_e$ [ $10^{11}$ ]	3.09	3.65	3.61	3.09	3.65	3.61	1.76	2.5	3.0	2.59	1.76	2.5	3.0	2.59
Emittance at IP-horizontal $\epsilon_x$ [nm·rad]	48	18.68	6.12	48	20	6.9	32	18	6.8	2.2	32	18	6.8	2.2
Emittance at IP-vertical $\epsilon_y$ [pm·rad]	96	36	21.2	96	36	21.2	64	24	18.2	9.2	64	24	18.2	9.2
Betatron function at IP-horizontal $\beta_x$ [m]	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Betatron function at IP-vertical $\beta_y$ [mm]	1.2	1.2	1.2	1.2	1.2	1.2	1	1	1	1	1	1	1	1
Transverse beam size at IP-horizontal $\sigma_x$ [ $\mu$ m]	196	122.2	70	196	122.2	70	160	120	73.8	41.95	160	120	73.8	41.95
Transverse beam size at IP-vertical $\sigma_y$ [ $\mu$ m]	0.339	0.208	0.159	0.339	0.208	0.159	0.253	0.155	0.135	0.096	0.253	0.155	0.135	0.096
Bunch length $\sigma_s$ [mm]	2.65	2.65	2.65	2.65	2.65	2.65	2.44	2	2	1.8	2.44	2	2	1.8
Beam-beam parameter $\xi_x$	0.032	0.056	0.112	0.032	0.056	0.112	0.028	0.04	0.084	0.154	0.028	0.04	0.084	0.154
Beam-beam parameter $\xi_y$	0.028	0.049	0.074	0.028	0.049	0.074	0.022	0.038	0.057	0.084	0.022	0.038	0.057	0.084
Hourglass factor $F_h$	0.68	0.68	0.68	0.68	0.68	0.68	0.654	0.706	0.706	0.732	0.654	0.706	0.706	0.732
Luminosity per IP $L$ [ $10^{34}\text{cm}^{-2}\text{s}^{-1}$ ]	0.22	0.82	1.82	12.5	4.08	1.82	0.23	1.09	2.93	1.4	18.6	6.52	2.93	1.4
RF voltage $V_{rf}$ [GV]	0.21	2.53	4.98	0.21	2.53	4.98	0.36	1.33	2.93	9.8	0.36	1.33	2.93	9.8
RF frequency $f_{rf}$ [GHz]	0.7	1.3	1.3	0.7	1.3	1.3	0.7	1.3	1.3	1.3	0.7	1.3	1.3	1.3
Synchrotron tune $Q_s$	0.017	0.127	0.091	0.017	0.127	0.09	0.036	0.064	0.051	0.049	0.036	0.064	0.051	0.049
Energy spread $\sigma_{\delta,SR}$ [%]	0.05	0.09	0.13	0.05	0.09	0.13	0.04	0.07	0.10	0.15	0.04	0.07	0.10	0.15
Average number of photons emitted per electron during the collision $n_\gamma$	0.065	0.122	0.209	0.065	0.122	0.209	0.045	0.086	0.167	0.253	0.045	0.086	0.167	0.253

### 4.3 Choice of the geometry

At the moment, different geometric imagines of the future circular collider are warmly under discussion. There are two attracting plans, one is CEPC which is 50km at the preliminary design and the other one is FCC-ee which is 100km. From TABLE 1, one would find that the luminosity per IP in 100km imagine is only 1.6 times than 50km scheme. It is not economic to ex-

pense double money to gain about 60% luminosity. However, the 100km imagine could cover the energy range of 175GeV which contains  $t\bar{t}$  experiment and make it possible to upgrade to a 100TeV proton-proton collider. The advantage of a larger geometric is the possibility of higher energy frontier but not luminosity gain. So, one question comes that what size is a better choice for a Higgs factory right now?

Table 2. Parameter study for Z and W-pole under baseline design of CEPC.

Parameters	Z-pole			W-pole			
$E[\text{GeV}]$	45.5			80			
$C[\text{km}]$	50						
$N_{\text{IP}}$	2						
$P[\text{MW}]$	0.89	1.85	4.06	10.0	12.5	20.8	45.8
$U_0[\text{GeV}]$	0.62			0.59			
$I[\text{mA}]$	14.22	29.6	74.1	16.8	21.0	35.0	77.0
$N_b$	48	100	220	48	60	100	220
$N_e[10^{11}]$	3.09			3.65			
$\epsilon_x[\text{nm}\cdot\text{rad}]$	48			18.68			
$\epsilon_y[\text{pm}\cdot\text{rad}]$	96			36			
$\beta_x[\text{mm}]$	0.8			0.8			
$\beta_y[\text{mm}]$	1.2			1.2			
$\sigma_x[\text{m}]$	196			122.25			
$\sigma_y[\text{m}]$	0.34			0.208			
$\xi_x$	0.032			0.056			
$\xi_y$	0.028			0.049			
$\sigma_s[\text{mm}]$	2.65			2.65			
Hourglass factor	0.68			0.68			
$L[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	0.22	0.466	1.02	0.82	1.02	1.70	3.74

No matter 50km or 100km, they are general imagines for the future circular collider. It is the circumference and filling factor that affect the synchrotron radiation.

Table 3. Higgs Factory in different circumference.

Parameters	120		
Beam energy $E[\text{GeV}]$	120		
Circumference $C[\text{km}]$	50	70	100
Number of IP $N_{\text{IP}}$	2		
Bending radius $\rho[\text{km}]$	6.094	8.60	10.0
SR power/beam $P[\text{MW}]$	50		
SR loss/turn $U_0[\text{GeV}]$	3.01	2.13	1.84
Beam current $I[\text{mA}]$	16.6	23.4	27.6
Bunch number $N_b$	48	114	192
Bunch population $N_e[10^{11}]$	3.61	3.0	3.0
Horizontal emittance $\epsilon_x[\text{nm}\cdot\text{rad}]$	6.12	6.36	6.8
Vertical emittance $\epsilon_y[\text{pm}\cdot\text{rad}]$	21.2	20.0	18.2
Betatron function at IP-vertical $\beta_y[\text{mm}]$	1.2	1.2	1.0
Betatron function at IP-horizontal $\beta_x[\text{mm}]$	0.8	0.8	0.8
Transverse beam size $\sigma_x[\text{m}]$	70.0	71.3	73.8
Transverse beam size $\sigma_y[\text{m}]$	0.160	0.155	0.135
Beam-beam parameter $\xi_x$	0.112	0.090	0.084
Beam-beam parameter $\xi_y$	0.074	0.062	0.057
Bunch length $\sigma_s[\text{mm}]$	2.65	2.35	2.00
Hourglass factor	0.68	0.71	0.71
Luminosity $L[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	1.82	2.25	2.93

We compare the parameters in 50km, 70km and 100km,

the results are shown in TABLE 3.

Using the data in TABLE 3, we give the relationship between the luminosity and circumference, which obey a power law as:

$$L[\text{cm}^{-2}\text{s}^{-1}] \sim 0.11833 \times C[\text{km}]^{0.69612} \quad (7)$$

And it is clearer to show it in Fig. 1.

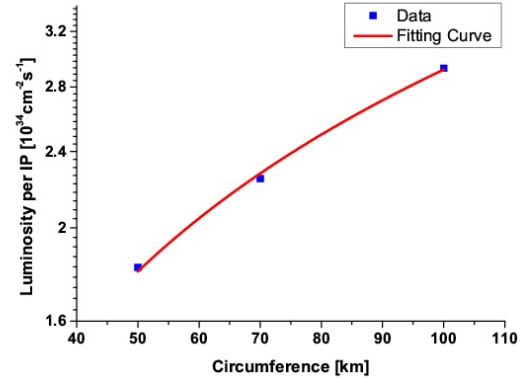


Fig. 1. Power law of Luminosity v.s. Circumference.

As is known to all, the synchrotron radiation is directly connected with bending radius when the beam energy is set. Filling factor, which is defined as the length of dipoles in a ring over the circumference of the whole ring, would have an influence on the luminosity under a certain circumference. We choose 50km as example, the relationship between luminosity and filling factor is listed in TABLE 4. The fitting result is in eq.(8).

$$L[\text{cm}^{-2}\text{s}^{-1}] \sim 0.18097 \times \zeta[\%]^{0.53155} \quad (8)$$

Table 4. Filling Factor.

Parameters							
Filling Factor $\zeta$ [%]	70	74	77	78	80	90	100
Luminosity $L[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	1.73	1.78	1.82	1.83	1.85	2.02	2.07

And it is clearer to show it in Fig. 2.

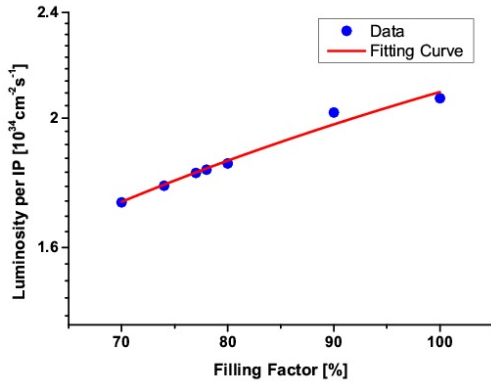


Fig. 2. Power law of Luminosity v.s. Filling Factor. The data points are from 50km design.

It is the circumference and filling factor that affect the synchrotron radiation. We compare the parameters in 50km, 70km and 100km, the results are shown in TABLE 3.

In order to evaluate the geometry choice, we combine eq.(7) and eq.(8) and give the result in Fig. 3. According to Fig. 3, the longer in circumference and the higher in filling factor, the higher of luminosity. However, double size in circumference does not give a twice gain in luminosity from eq.(7), and a suitable filling factor should be taken into consideration because one should make room for other insertions around the ring. For a 50km design of circular electron positron collider, a filling factor from 60% to 80% is reason due to the design of other function insertions. And our choice is marked with a diamond in Fig. 3.

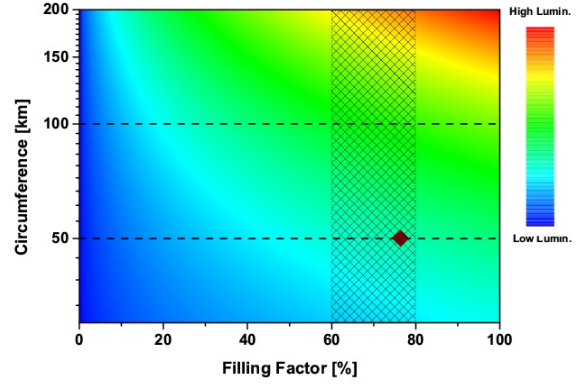


Fig. 3. The relationship of luminosity with circumference and filling factor. The shadow area shows the reasonable choice from experience. The diamond represents the choice of 50km CEPC design.

Here we compare the nominal performance of CEPC-SPPC with LHC and FCC [7, 8], and show the luminosity vs. energy in Fig. 4. For CEPC and FCC-ee, the synchrotron radiation power limits the luminosity. And the expected luminosity in FCC-ee might be too high because the beam-beam parameter in [7] exceeds the beam-beam limit according to the theory in [3]. The compare results are shown in TABLE 5.

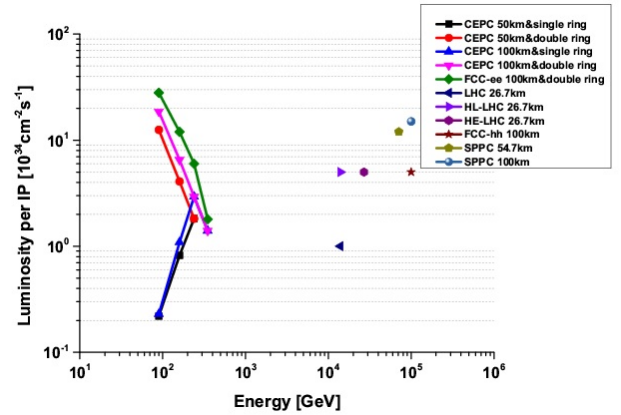


Fig. 4. Comparing the luminosity potential of CEPC-SPPC with LHC and FCC. The results are measured by the Luminosity per IP vs. Energy.

Table 5. Compare the CEPC with FCC-ee and LEP2.

Parameters	LEP2	FCC-ee				CEPC
Circumference[km]	26.7	100				50
Bending radius[km]	3.1	11				6.094
Momentum acceptance	0.01	0.02				0.02
Beam energy[GeV]	104	45.5	80	120	175	120
IP number $N_{IP}$		4				2
Beam current[mA]	3.04	1450	152	30	6.6	17.45
Bunches per beam	4	16700	4490	1360	98	48
Bunch population[ $10^{11}$ ]	4.2	1.8	0.7	0.46	1.4	3.79
Transverse emittance $\epsilon$						
-Horizontal[nm]	22	29.2	3.3	0.94	2	6.9
-Vertical[pn]	250	60	7	1.9	2	21.2
Momentum comp.[ $10^{-5}$ ]	14	18	2	0.5	0.5	0.729
Betatron function at IP $\beta$						
-Horizontal[m]	1.2	0.5	0.5	0.5	1	0.8
-Vertical[mm]	50	1	1	1	1	1.2
Beam size at IP $\sigma[\mu\text{m}]$						
-Horizontal	182	121	26	22	45	74.3
-Vertical	3.2	0.25	0.13	0.044	0.045	0.16
Energy loss/turn[GeV]	3.34	0.03	0.33	1.67	7.55	3.01
SR power/beam[MW]	11	50				50
Total RF voltage[GV]	3.5	2.5	4	5.5	11	4.98
RF frequency[MHz]	352	800				700
Synchrotron tune $Q_s$	0.083	0.65	0.21	0.096	0.1	0.09
Hourglass factor	1	0.64	0.77	0.83	0.78	0.68
Luminosity/IP[ $10^3\text{cm}^{-2}\text{s}^{-1}$ ]	0.012	28	12	6	1.8	1.89
Beam-beam parameter						
-Horizontal	0.04	0.031	0.06	0.093	0.092	0.105
-Vertical	0.06	0.03	0.059	0.093	0.092	0.073
Beam-beam limit(vertical)/IP	0.064	0.015	0.026	0.038	0.057	0.073

## 5 Summary

In this paper, we give the results of CEPC performances with different collision energies and geometric layouts, including Z and W and Higgs energy run for 50km and 100km(covered  $t\bar{t}$ ) circumference in both single ring and double ring schemes. When limiting the synchrotron radiation power to 50MW and adopting Pretzel Orbit, it is economic to construct a 50km circular electron positron collider rather than a 100km one, and one beam pipe for CEPC serving as a Higgs factory could

achieve the same luminosity with double ring scheme. However, under these conditions, it is not so good to expect CEPC working in Z or W poles with high luminosity. What's more, we studied the relationship of luminosity with circumference and filling factor, which could evaluate the geometry choice. A large size of circular collider ring would be more attracting for its ability to upgrade to higher energy proton-proton collider. Also, we compare the nominal performance of the CEPC-SPPC with LHC and FCC, which shows future landscape in the high luminosity and high energy frontier.

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## References

- 1 CEPC-SPPC Preliminary Conceptual Design Report, The CEPC-SPPC Study Group, IHEP-CEPC-DR-2015-01.
- 2 D. Wang et al, "Optimization Parameter Design of a Circular  $e^+e^-$  Higgs Factory", CHINESE PHYSICS C 37 097003.
- 3 J. Gao, "Emittance growth and beam lifetime limitations due to beamCbeam effects in  $e^+e^-$  storage ring colliders", Nucl. Instr. and methods A, Volume 533, Issue 3(2004) p. 270-274.
- 4 J. Gao, "Review of some important beam physics issues in electron positron collider designs", Modern Physics Letters A Vol. 30, No. 11 (2015).
- 5 V. I. Telnov, "Restriction on the energy and luminosity of  $e^+e^-$  storage rings due to beamstrahlung", Phys. Rev. Lett. 110, 114801.
- 6 J. Gao, IHEP-AC-Note-2013-012.
- 7 FCC-ee design study, <http://tlep.web.cern.ch/content/machine-parameters>.
- 8 FCC-hh design study, <http://tlep.web.cern.ch/content/fcc-hh>.